Geneva, 17^{th} October 2022

Ultra-light FIPs: What we know from stars/supernovae/neutron stars/white dwarfs/etc

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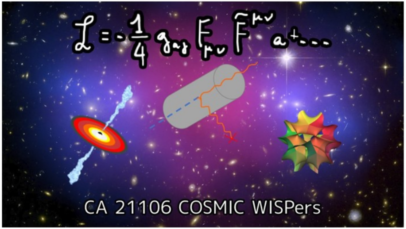
COSMIC WISPers in the Dark Universe:

Theory, astrophysics and experiments



more info at https://www.cost.eu/actions/CA21106/

FIPs: the fabulous five

P. Agrawal *et al.* Eur. Phys. J. C **81** (2021) no.11, 1015

FIPs are a window on high energy fundamental physics

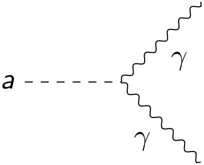
Portal	Coupling
Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Axion-like particles, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Dark Higgs, S	$(\mu S + \lambda_{\rm HS} S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$
milicharged particle, χ	$\epsilon A^\mu \bar{\chi} \gamma_\mu \chi$

Stars are unique factories of FIPs

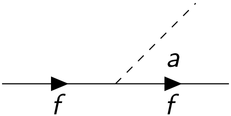
Axions and Axion-Like Particles

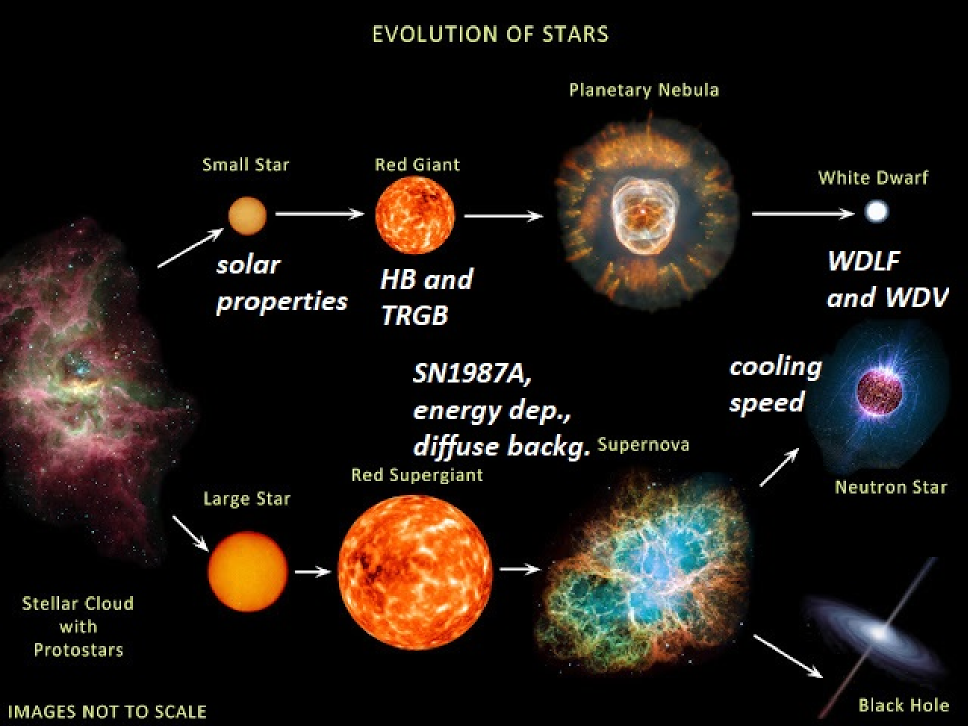
Dark matter candidates and solution of the Strong CP problem

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \quad g_{a\gamma} = C_\gamma \frac{\alpha}{2\pi f_a}$$



$$\mathcal{L}_{af} = \frac{g_{af}}{2m_f}\bar{\Psi}\gamma^\mu\gamma^5\Psi\, \partial_\mu a \quad g_{af} = C_f \frac{m_f}{f_a}$$

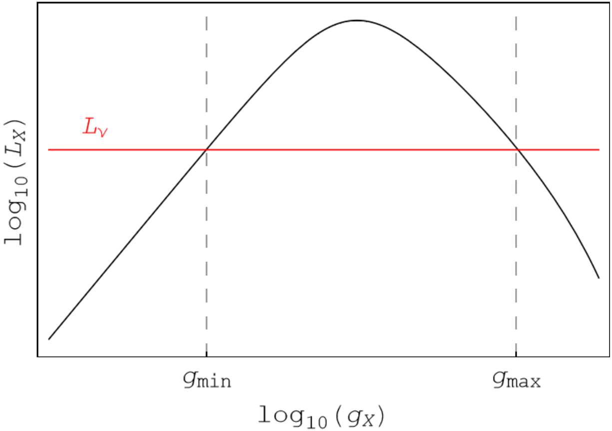



EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
solar properties
HB and TRGB
WDLF and WDV
SN1987A, energy dep., diffuse backg.
cooling speed
Supernova
Red Supergiant
Large Star
Neutron Star
Stellar Cloud with Protostars
Black Hole
IMAGES NOT TO SCALE

The energy-loss argument

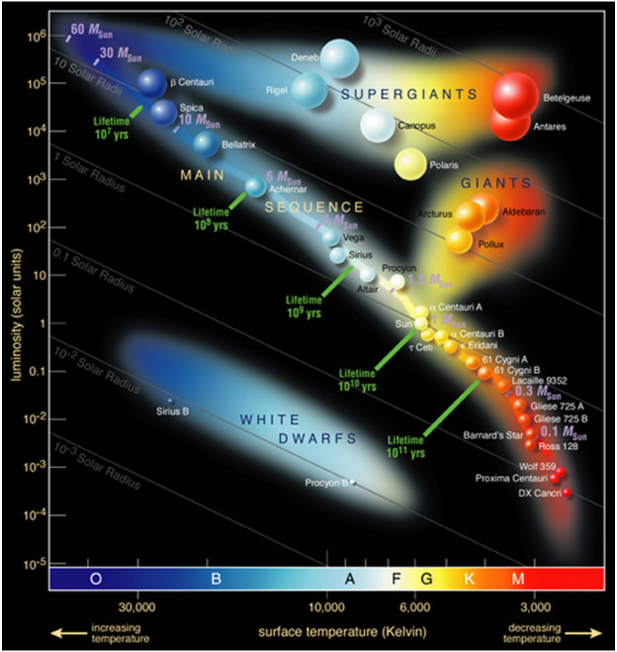
G. Raffelt, Lect. Notes Phys. **741** (2008)

Stars produce FIPs which escape, draining energy



Feeble means strong impact on the stellar evolution!

The Hertzsprung-Russell diagram

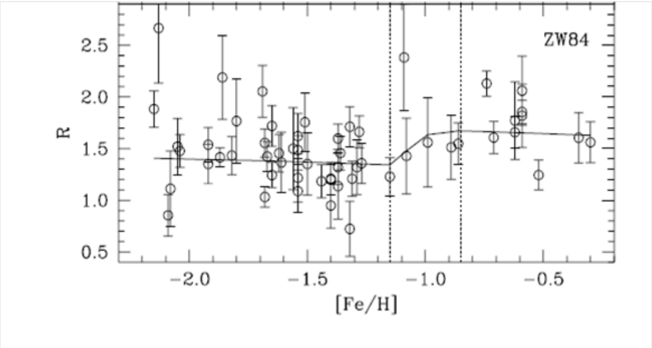


Measuring the duration of stellar phases: the R parameter

M. Salaris *et al.*, Astron. Astrophys. **420** (2004), 911-919

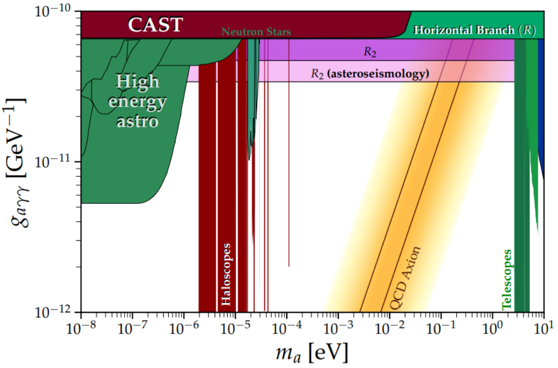
Observations on Globular Clusters measure the R parameter

$$R = \frac{N_{\rm HB}}{N_{\rm RGB}} = \frac{\tau_{\rm HB}}{\tau_{\rm RGB}} = 1.39 \pm 0.03$$



Globular Cluster constraints for light ALPs

- $g_{a\gamma} < 0.65 \times 10^{-10}\,\text{GeV}^{-1}$ at 95% CL
  A. Ayala *et al.*, Phys. Rev. Lett. **113** (2014) no.19, 191302
- $g_{a\gamma} < 0.47 \times 10^{-10}\,\text{GeV}^{-1}$ at 95% CL
  M. J. Dolan *et al.*, [arXiv:2207.03102 [hep-ph]]

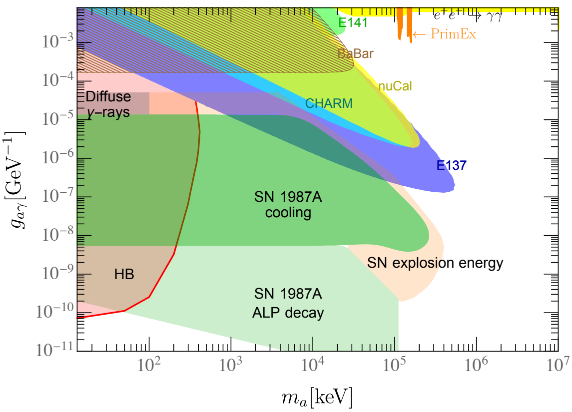


Improvement: use of $R_2 = N_{\rm AGB}/N_{\rm HB} = 0.117 \pm 0.005$
AGB are hotter than HB, better probe!?

Globular Cluster constraints for heavy ALPs

G. Lucente *et al.*, Phys. Rev. Lett. **129**, no.1, 011101 (2022)

Interplay with SN bound and beam dump experiments in this region

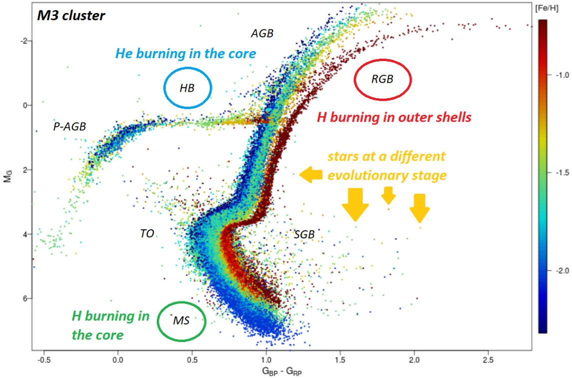


Measuring the duration of stellar phases: RGB tip

O. Straniero *et al.*, Astron. Astrophys. **644** (2020), A166

F. Capozzi and G. Raffelt, Phys. Rev. D **102** (2020) no.8, 083007

Brighter endpoint of RG in case of exotic losses



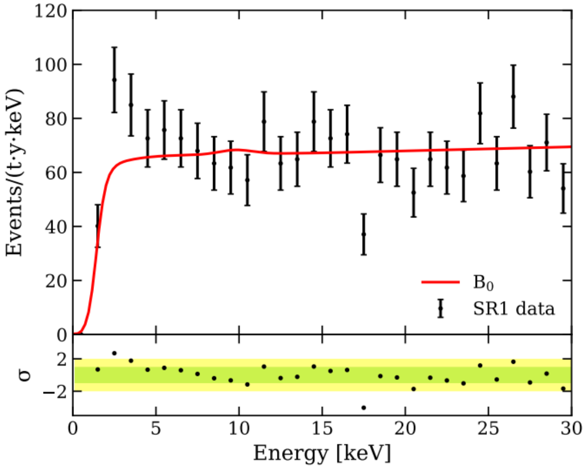
Axion bound: $g_{ae} < 1.3 - 1.48 \times 10^{-13}$

Neutrino bound: $\mu_\nu < 1.2 \times 10^{-12} \mu_B$

What about the XENON1T excess?

E. Aprile *et al.* [XENON], Phys. Rev. D **102** (2020) no.7, 072004

Anomaly explained in terms of solar axions, neutrino magnetic moment, axion or dark photon DM

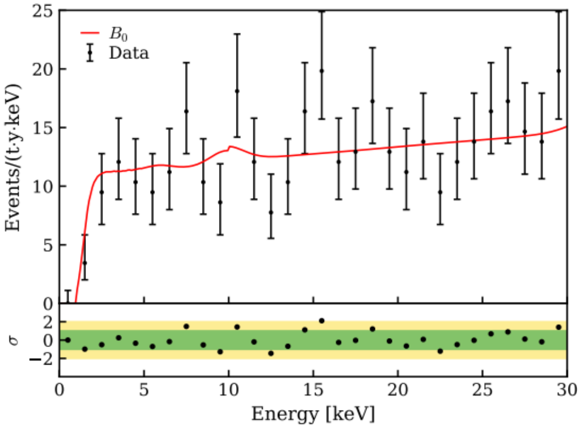


And XENONnT?

E. Aprile *et al.* [XENON], [arXiv:2207.11330 [hep-ex]].

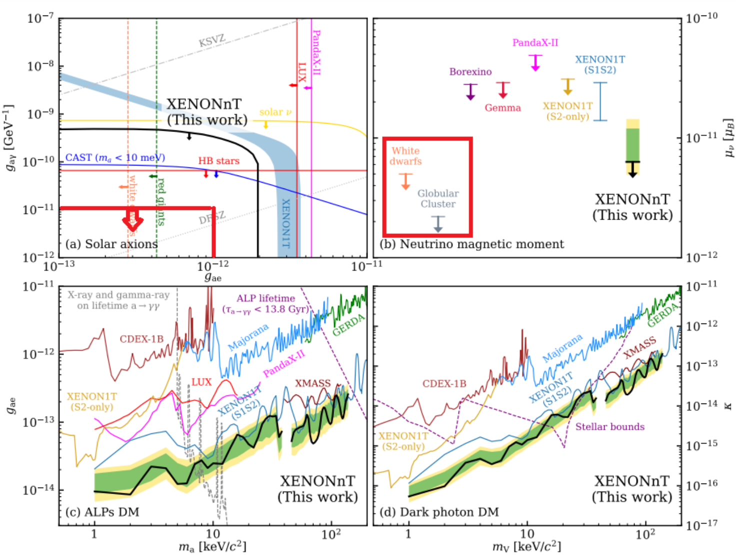
Axions with $g_{ae} \sim 3 \times 10^{-12}$????

see L. Di Luzio *et al.*, Phys. Rev. Lett. **125** (2020) no.13, 131804



No anomalies in XENONnT

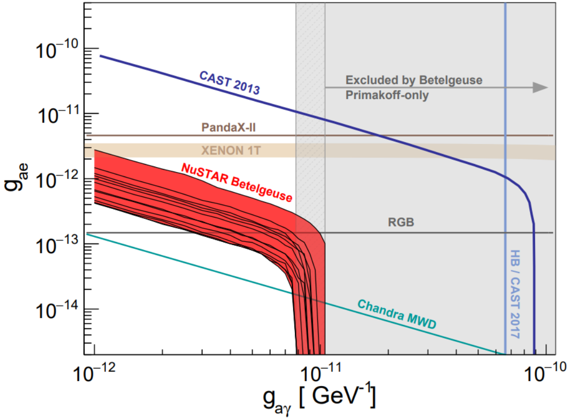
XENONnT Bounds



Remarks

M. Xiao *et al.*, [arXiv:2204.03121 [astro-ph.HE]]

Constraint for light ALPs ($m_a \lesssim 10^{-10}$ eV) from Betelgeuse observations



We'll discuss soon the WD bound on neutrino magnetic moment...

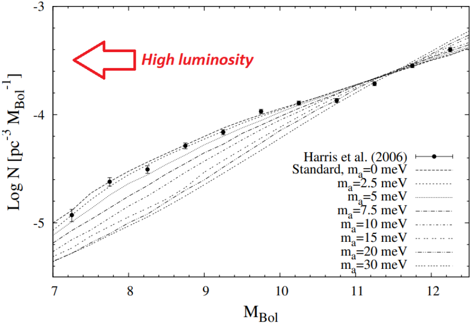
Measuring the duration of stellar phases: White Dwarf luminosity function

M. M. Miller Bertolami *et al.*, JCAP **10** (2014), 069

WD cooling might reveal FIPs

$$\frac{dN_{\mathrm{WD}}}{dV\,dL} \sim \frac{1}{L_\gamma + L_\nu + L_x}$$

Axions produced by $e^- I \to e^- I a$ and $\gamma e^- \to a e^-$



Bound $g_{ae} < 2.8 \times 10^{-13}$

Constraint on neutrino magnetic moment

A. H. Córsico *et al.*, JCAP **08**, 054 (2014)

Enhancement of the plasmon decay process

Bound on Neutrino Magnetic Moment

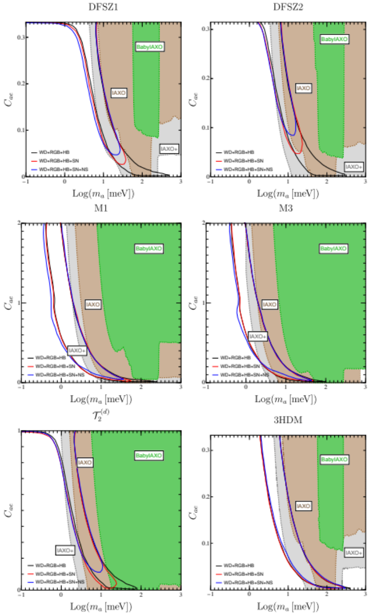
$$\mu_\nu < 5 \times 10^{-12} \mu_B$$

Not only bounds...

L. Di Luzio *et al.*, JCAP **02** (2022) no.02, 035

Star	Hint	Bound
Sun	No Hint	$g_{\gamma 10} \leq 2.7$
WDLF	$g_{e13} = 1.5^{+0.3}_{-0.5}$	$g_{e13} \leq 2.1$
WDV	$g_{e13} = 2.9^{+0.6}_{-0.9}$	$g_{e13} \leq 4.1$
RGBT (22 GGCs)	$g_{e13} = 0.60^{+0.32}_{-0.58}$	$g_{e13} \leq 1.5$
RGBT (NGC 4258)	No Hint	$g_{e13} \leq 1.6$
HB	$g_{\gamma 10} = 0.3^{+0.2}_{-0.2}$	$g_{\gamma 10} \leq 0.65$
SN 1987A	No Hint	$g_{aN} \lesssim 9.1 \times 10^{-10}$
NS (CAS A)	No Hint	$(g_{ap}^2 + 1.6\, g_{an}^2)^{1/2} \lesssim 1.0 \times 10^{-9}$
NS (CAS A)	No Hint	$g_{an} \lesssim 3 \times 10^{-10}$
NS (HESS)	No Hint	$g_{an} \leq 2.8 \times 10^{-10}$

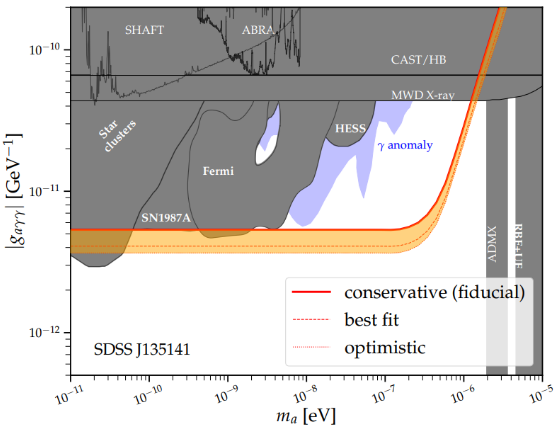
… that will be probed by IAXO



Magnetic white dwarf bound

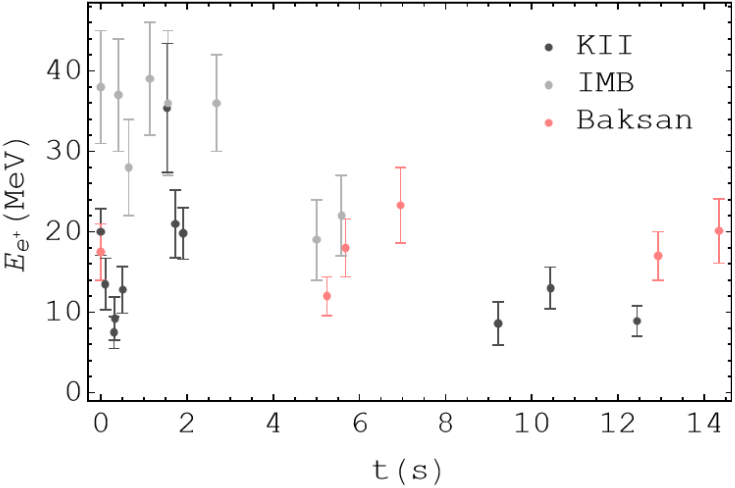
C. Dessert *et al.*, Phys. Rev. D **105** (2022) no.10, 103034

ALP-photon conversion generate a net polarization



Measuring the duration of stellar phases: Supernova cooling

From the few $\bar{\nu}_e p \to n e^+$ events of SN 1987A we know that...

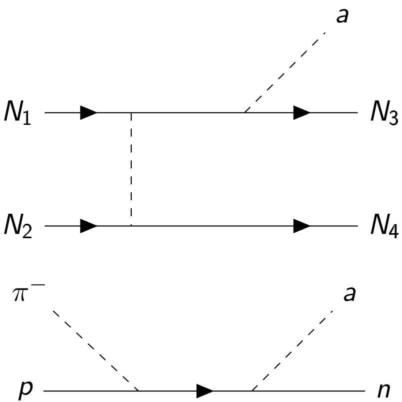


$\sim 10^{53}$ erg emitted as neutrinos with energy $\sim O(15\,\text{MeV})$ in $\sim 10\,\text{s}$

The SN axion bound

PC, B. Fore *et al.*, Phys. Rev. Lett. **126** (2021) no.7, 071102

SN axions are produced by nucleon-axion bremsstrahlung and pion conversion

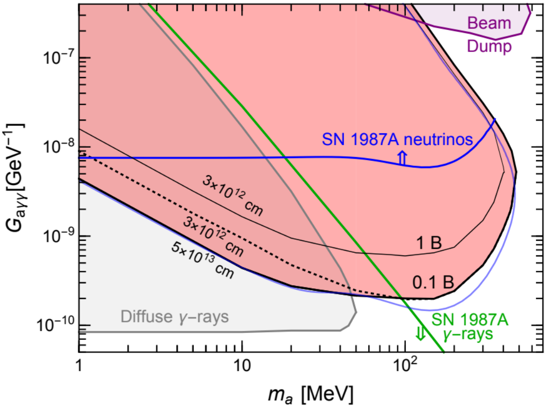


$\text{Bound}: m_a \lesssim 12 \text{ meV}$

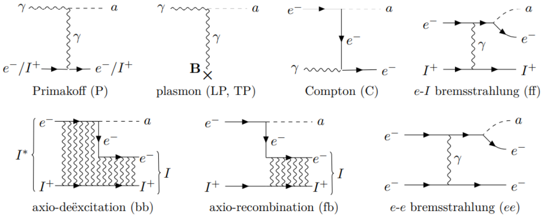
Explosion energy constraint

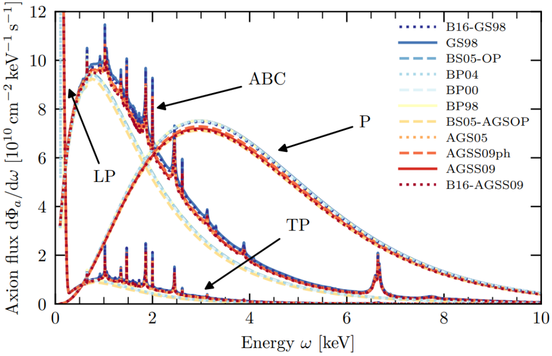
A. Caputo *et al.*, Phys. Rev. Lett. **128**, no.22, 221103 (2022)

The energy deposited by ALPs must be smaller than $\sim 10^{50}$ erg



News from the Sun

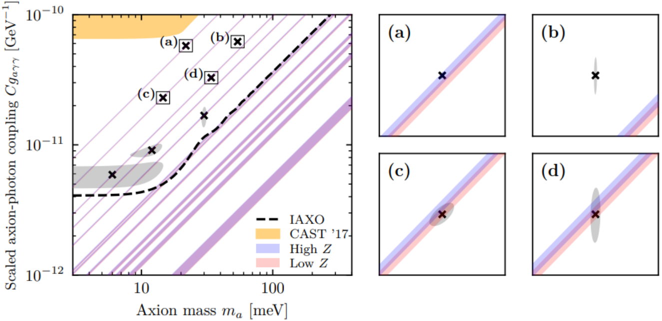




Discovery potential of IAXO

S. Hoof *et al.*, JCAP **09** (2021), 006

Unique determination of the axion model is possible

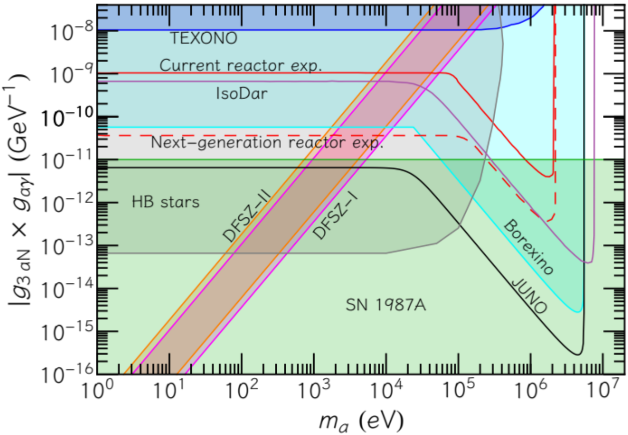


It might also probe solar properties

Solar axions with scintillation neutrino detectors

G. Lucente *et al.*, [arXiv:2209.11780 [hep-ph]].

Borexino probes $p + d \to {}^3\mathrm{He} + a$

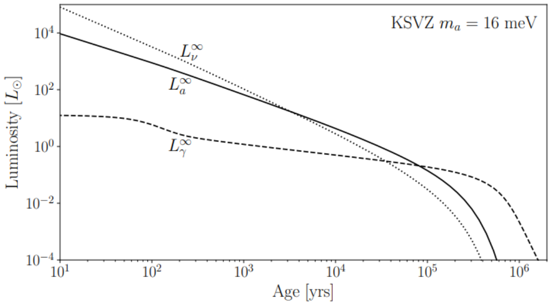


Huge improvement with JUNO

Limits on QCD axions from NS

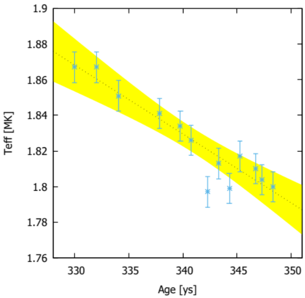
M. Buschmann *et al.* Phys. Rev. Lett. **128** (2022) no.9, 091102

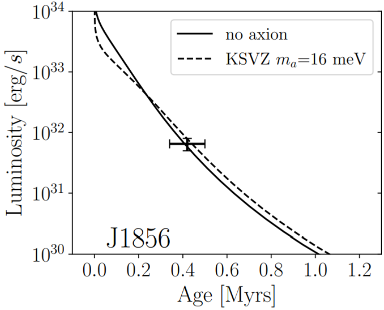
$NN \to NNa$ and breaking Cooper pairs produce axions in neutrons stars



$\sim 10^5$ yr is an axion-dominated period

Young vs Old NS





The obtained constraints are:

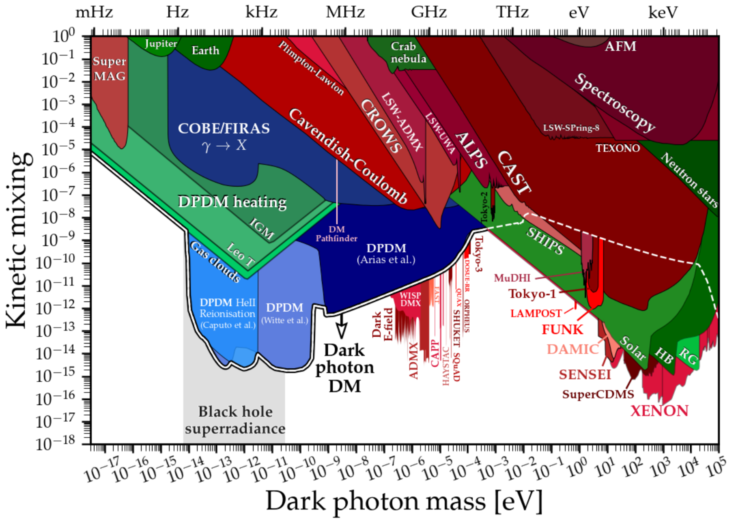
- Cas A (300 yr): $m_a < 20$ meV
  L. B. Leinson, JCAP **09** (2021), 001
- Magnificent Seven (10^5 yr): $m_a < 16$ meV
  M. Buschmann *et al.*, Phys. Rev. Lett. **128** (2022) no.9, 091102

Dark Photon constraints

H. An *et al.*, Phys. Lett. B **725** (2013), 190-195

A. Caputo *et al.*, Phys. Rev. D **104** (2021) no.9, 095029

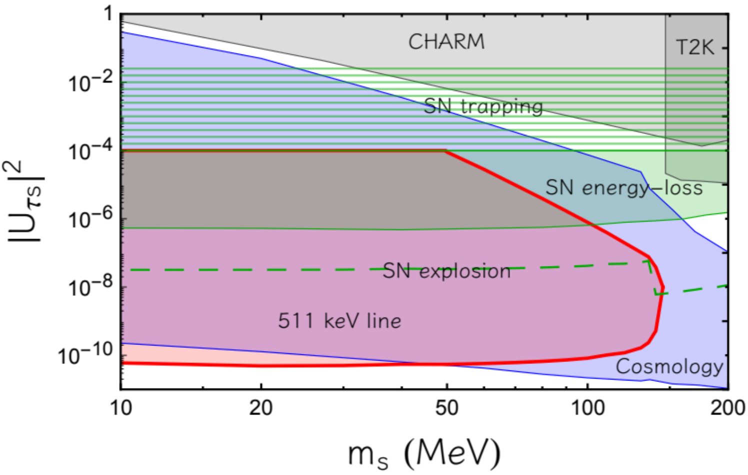
The production of DP is possible in stars



Bounds on sterile neutrinos

F. Calore *et al.*, Phys. Rev. D **105** (2022) no.6, 063026

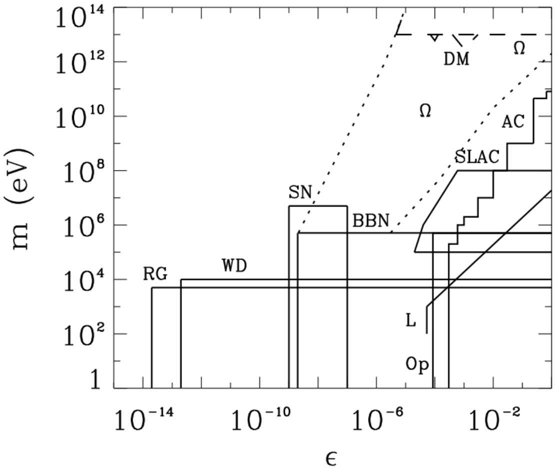
Production by $\nu\nu \to \nu_s\nu$ and decay $\nu_s \to \nu e^+ e^-$



Bounds on millicharged particles

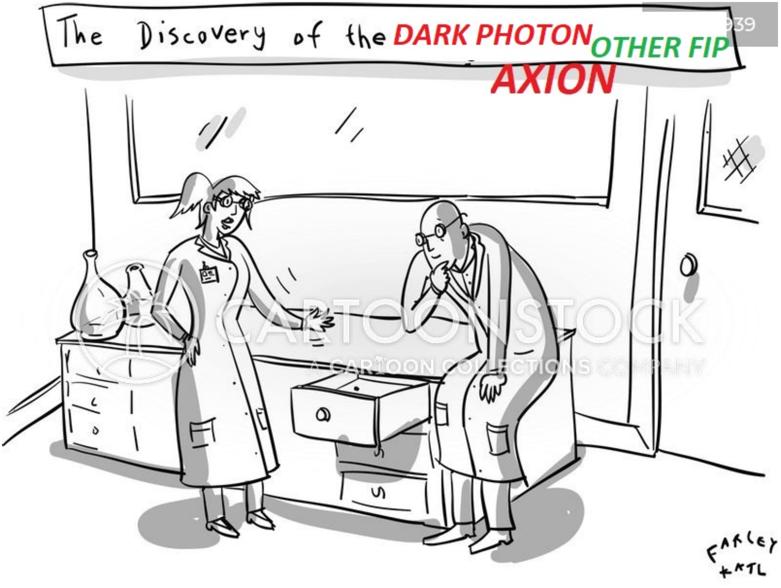
S. Davidson *et al.*, JHEP **05** (2000), 003

Stellar bounds, once more, are probing the smallest couplings



Production $\gamma \to f\bar{f}$

Conclusions



"Always the last place you look!"